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Abstract

Considerable amounts of data are collected on the UK's stock of bridges. Much of these data are collected to inform the planning and scope of maintenance activities. This paper reports on the results of a series of semi-structured interviews with 17 individuals involved in UK bridge asset management and data collection activities to explore how such data are used in practice. A wide spectrum of organisations and industrial sectors is represented in this dataset. Hierarchical Process Modelling was used to characterise, the UK's bridge management system and define the processes and sub-processes involved in the management of bridges. Key quotations are used from the interviews to reveal the state of data collection and use in UK bridge infrastructure from the perspective of those directly involved. The study concludes that there is significant variation within the industry of the use of visual inspection data and that formal Structural Health Monitoring (SHM) remains relatively rare. Furthermore, there is a need to develop a new unifying paradigm that will frame the efficient and effective application of emerging artificial intelligence and data science enabled (i.e. 'smart') condition monitoring techniques to bridge management.

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1. INTRODUCTION

The use of data in bridge management organisations is an important topic as the civil engineering profession seeks to understand the potential impacts and challenges of emerging artificial intelligence and data science enabled (‘smart’) condition monitoring techniques. The United Kingdom has an ageing stock of infrastructure, which has been referred to as an ‘asset time bomb’ (Thurlby, 2013). Making better use of collected data of bridge condition may assist with better management and maintenance of a nation’s bridge stock. The systems and processes by which data is used within bridge management, especially when planning maintenance interventions, are often not clearly reported in the literature as usually these processes are unique and internal to specific organisations. This paper aims to use data from a series of semi-structured interviews with a representative set of individuals who are involved in bridge management at various organisational levels to ‘map’ the system of bridge management, understand what data is collected and how it is used. This information is then used to gauge how well prepared the UK bridge management sector is for the emergence of smart condition monitoring techniques.

Preliminary findings from this study have been reported in the conference paper of Bennetts et al (2016). This paper gives the full set of results from the study. The findings are presented in two forms:

(a) Key quotations from a series of semi-structured interviews (explained in more detail in Section 2.1);

(b) Hierarchical Process Models (HPM) to capture what goes on and why with bridge management in the UK (explained in more detail in Section 2.2).

For further details on the ‘Management of Bridges Project’ see the thesis of Bennetts (2019) which also includes some of the work reported in this paper.

2. METHODOLOGY

2.1 Semi-Structured Interviews

This study involved the use of semi-structured interviews of people engaged in bridge management activities in the UK. In such a study, the interviewees should be representative of UK bridge owners and managers (i.e. the population) (e.g., Oppenheim, 1992). Therefore, those interviewed were chosen to be representative of those involved or who have a professional interest in UK bridge management. The interviewed group included policy setters in major organisations; inspectors, and managers of individual assets. All modes of transport (e.g., rail and highway); the level of organisational remit (i.e. strategic, city region and local authority) and links in the supply chain were sampled. In total, 14 interviews were conducted, with 17 participants. Table 1 gives the organisational roles and sectors of those interviewed. Throughout this paper, quotations from those interviewed are presented and are referenced using the notation shown in Table 1 (e.g., **C1**) printed in brackets following the quotation. For brevity, the paper is necessarily selective as the transcripts of the interviews are anonymous.

Standardisation of the interviews was achieved by using a common interview protocol to explore the important research topics and areas of interest for the investigation. All the interviews were performed by the first author, and care was taken to avoid leading the interview candidates. The research consciously adopted a ‘mixed-methods’ approach, combining hypothesis-led positivist style questions such as “*what data do you collect on your structures*“ which expect a closed form answer, with response-led lines of questioning and discussion, where the interview protocol was used to define the theme of the discussion, rather than the precise questions used. This latter style of questioning for themes such as “*how does your organisation make decisions*“ represents a Grounded Theory (Glaser and

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Strauss, 1967) approach. The interview protocol is included as Table 2. The interviews were recorded digitally and then analysed by ‘coding’ against research questions and emerging themes in the audio files (e.g., Saunders *et al.* 2009). This ‘coding’ of interview transcripts or audio files consists of highlighting snippets of the interview which relate to each of the research questions or emerging themes identified during the analysis of the transcripts. A series of codes (Table 3) were set up and these were then applied to relevant sections of the interview audio files. The coding schema (Table 3) was developed inductively and updated as the interviews were processed. This resulted in an iterative process as already coded files were reviewed and reflected upon as new files were analysed and themes emerged. Traditionally these approaches would have been applied manually with page markers and highlighters in the transcripts. In this work, Dedoose.com, a Computer-aided qualitative data analysis software (CAQDAS) package, was used to transcribe the audio and apply the codes as a digital pack of highlighters and bookmarks in the transcript files. The software is able to maintain a link to the underlying interview recording in-line with the transcription so that when it came to reviewing the emerging themes and conclusions, the relevant snippets from each of the interviews could be viewed alongside each other and played to check that the context and tone of the quotes before inclusion in the narrative. By enabling each relevant extract to be reviewed alongside others, the software helped to reduce bias between the interviews and allowed audit the key results within the authors. All the interview extracts have been carefully anonymised. In some cases, the quotations have been slightly altered to improve the grammar but with the original meaning preserved.

2.2 Hierarchical Process Modelling

‘Complicated processes’ can be reduced to a hierarchy of increasingly simple sub-processes (Hall et al. 2004). In the hierarchical tree structure, child processes answer the question *"how* *do we do this process?"*, and parent processes answer the question *"why do we do this process?"* This type of modelling by individual '*experts*' has been applied in various attempts to model the performance of civil engineering systems having a significant degree of complexity and uncertainty (e.g., Blockley and Godfrey 2000, Hall *et al.* 2004).

In many examples (e.g. Davis and Hall 2003, Blockley et al. 2012), the technique is combined with Italian Flag Notation and Interval Probability Theory to quantify the uncertainty in decision making systems. However, it is stressed that the models presented in this paper are ontological rather than mathematical/computational, i.e. the word 'model' refers to a conceptual model of the interconnected processes of bridge management in the UK to aid understanding of the way in which processes interlink. The novelty of the work lies in the interview results and the topography of the hierarchical process diagrams not in the further development or justification of HPM approaches.

Hierarchical Process Modelling is a method of eliciting and formalising 'expert' knowledge and heuristics. However, it is not anticipated that any single '*expert*' would be able to produce a model of the UK's Bridge Management system encompassing all its facets because there are many different agents within the system, which each have different visibility and perspectives on the whole system. Davis *et al.* (2010) report successful use of group sessions for building Hierarchical Process Models when *"no single person can understand all aspects, issues and variables of such an intricate problem"*. Lane (1992) argues that the approach of individuals building conceptual systems models as '*experts*' can reduce stakeholder trust in the models and chances of making successful interventions. Flaig and Lark (2000) published a study of Bridge Management Systems (BMS) in the UK after conducting an extensive set of interviews and concluded that "...*current systems are often too theoretical in the approach they take to the practical task of managing a bridge stock* ...".

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Reviewing the options for building models of the Bridge Management System, it was therefore considered preferable to hold group modelling sessions with stakeholders from different organisations in the system. However, in this case, because of the organisational and spatial distribution of the key stakeholders, it was not viable to convene a meaningful panel to engage in a group modelling exercise. Therefore, the process of group model building was distributed across a series of smaller, often individual, facilitated model building sessions. In this way, individual sessions were held with key actors to produce a model that captured their perspective on the overall system. These individual models were then synthesised by the author into one over-arching model which encompasses all the individual perspectives. The modelling sessions were introduced as part of the semi-structured interviews, with candidates introduced to an example of a simple Hierarchical Process Model for *'Being a Water plc'* and *'Owning a Dam'* as presented in Blockley *et al.* (2012). The interviewees were then given a sheet of paper printed with the starting point for a Bridge Management model as shown in Figure 1, this 'seed' was used a starting point and to set the context and scope for the interviewee's diagrams. These seeds were adjusted to reflect the sector and scope of each candidate's role.

3. THE BRIDGE MANAGEMENT PROCESS: MODELLING

At the top level, all of the processes identified by candidates could be categorised under three fundamental processes: 'understanding the stock'; 'making decisions'; and 'implementing interventions'. These fundamental processes operate within a framework that is defined by the organisation's higher-level objectives, industry codes of practice and standards and is bounded by budgetary constraints. Figure 2 shows the three identified core processes, which often follow sequentially (anti-clockwise in this diagram), and cyclically, in time and therefore could also be taken to represent a typical Action Research reflect-plan-act-observe-reflect cycle, as per Kemmis *et al.* (1988).

For strategic-level organisations, significant links and interactions were noted between the processes within the Bridge Management system and the operating environment, with some seeking to control the operating environment by justifying increases to budget, contributing to standards and informing objectives. In effect, these organisations have been able to expand their system boundary and engage in the national socio-political system to improve their position. For some organisations, a significant portion of the interviewed individual's efforts were reported to be dedicated to the creation and maintenance of relevant codes and standards. However, this has been taken to be activity outside the core process of managing bridges. Sections 4-6 give some selected key quotations from the semi-structured interviews which fall under the three identified top-level processes of the HPM: 'understanding the stock'; 'making decisions'; and 'implementing interventions'.

4. USES OF BRIDGE ASSET DATA: IMPLEMENTING INTERVENTIONS

Bridge managers have a relatively small number of fundamental intervention options open to them. They may: (i) Implement maintenance interventions to existing bridges to renew their condition; (ii) Improve existing structures to increase their carrying capacity (either in lane width, or load rating), or; (iii) Demolish or replace structures at the end of their service lives. Most bridge owners reported programmes of routine maintenance, and systems for reacting quickly to urgent safety-critical issues reported through inspections, user hot-lines or network control centres. Another key activity was reported to be maintaining an engaged and proactive supply chain, which was noted to be crucial to enabling cost effective interventions "*If you don't get the [implementation of interventions right] everything else will be a waste of* *time because you need a supply chain that are with you and like you*"(**C15**). Figure 3 shows the developed HPM for ‘Implementing interventions’. ‘Implementing interventions’ can be broken down into ‘managing supply chains’; ‘replacing structures’; ‘improving structures’ and ‘maintaining structures’.

5. USES OF BRIDGE ASSET DATA: UNDERSTANDING THE STOCK

Maintaining a deep and up-to-date understanding of the stock of bridges an organisation is responsible for is crucial to being able to effectively plan activities and expenditure to manage the risks caused by ageing infrastructure, environmental hazards, and accidental events. Maintaining this understanding comprises four key activities: compiling and maintaining an inventory of the structures an organisation is responsible for; monitoring and maintaining records of their condition; maintaining records of their capacity; and managing risks to safety or functionality. Figure 4 shows the branch of the developed HPM for ‘Understanding the Stock’ from which four primary nodes were identified: ‘compiling inventory’; ‘understanding condition’; ‘understanding capacity’ and ‘understanding risk’. Some key quotes related to understanding the stock are now presented.

5.1 Compiling Inventory and Recording Data

The majority of interviewees reported that their bridge information is held in dedicated databases which typically hold inventory, inspection and maintenance data. These databases often also hold the results of load-rating assessments and risk assessments such as for scour or road safety. The maturity of these tools varies, with a few organisations relying on spreadsheets for some aspects of their data management, while others have complex integrated IT solutions. Many participants mentioned either newly implemented or imminent IT solutions: “*we’re in the process of rolling it [the new system] out ...it pulls all those* *databases together, so we've got one version of truth*" (**C5**). On the development of a new system, another interviewee stated: "*well it's still in its infancy, I mean we've probably been running it for 3 or 4 years now and it's evolved slightly as well ...we've now got a refined approach ...we'll refine the process as well and keep reviewing it, and it'll become better and better and also we'll have more historical data to be able to verify against as well*" (**C2**).

5.2 Visual Inspection

Asset managers need a rational approach to allocate maintenance and upgrade resources. As a result, visual inspections are carried out to assess the level of deterioration of bridge assets (typically principal inspections, which involve up-close inspection of all elements to within touching distance are performed at six yearly intervals, but may the interval may be adjusted on a risk basis: HE, 2017, Network Rail 2017). Visual inspections are reliant on the interpretation (and judgement) of the bridge inspector on site and are carried out often in difficult conditions such as within confined spaces with poor lighting. Studies have shown that there is variability in the scores given by different inspectors during visual inspection and therefore the data itself suffers from inevitable fuzziness and variability (e.g., Moore et al. 2001; Graybeal et al. 2002; Lea and Middleton, 2002; Middleton, 2004). Bennetts et al. (2018a and 2018b) demonstrate with more recent data that, while variability in scores is evident for individual defects, visual inspection can capture deterioration rates at stock level. All the represented organisations in the survey set make use of visual inspection as the primary condition data source. Many organisations appear to see it as a key driver of the management of their structural assets. One interview stated: "*inspections are, really, the foundation for everything we do*" (**C3**). Most inspection recording protocols record condition data as the nature, severity and extent of the defects, mostly using the County Surveyors' Society system described in TSO 2007, or adaptations thereof. While using a similar

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approach, the rail sector records defect risk in terms of consequence and likelihood. Visual inspections are also used to record maintenance activities which may be linked to specific structural defects and the indicative costs allocated: "*we record suggested remedial works, indicative prices, that sort of thing*" (**C4**). Recently, many organisations have begun to extend the inspection intervals for some structures beyond 6 years on a risk basis: "*the cycle is dependent on risk, so if you've got a brand new concrete or weathering steel structure you might want to look at it less frequently*" (**C5**). One interviewee questioned if the frequent General Inspections which are more superficial in nature offer value in the current inspection regime. "*Take a General Inspection, I half think you're doing it for your own self conscious, I don't think there's much merit in it.*" (**C15**). Interestingly the rail sector's programme of inspections has been aligned with necessary inspections for an 18-year cycle of steady-state load rating assessments so that "*Every 18 years you will get an engineer doing an examination [whereas otherwise] ...our examiners are generally ex-trades[people]*" (**C5**). The need to ensure reliability of collected inspection data was noted by some interviewees: "*...subsequently we obviously make the decisions on it, and if you're making it on the basis of unreliable data then that's clearly poor practice*" (**C1**). Some interviewees noted that they had undertaken informal comparisons of the inspection results from different inspectors and found significant variation. Some interviewees discussed a lack of confidence in quality of inspections delivered by their suppliers: "*we are finding the quality of those inspections that we're getting done externally is ...inadequate*" (**C2**), and some participants are examining the possibility to change how their inspections are delivered: "*it may be that inspections are handled in-house or maybe with a contract that's separate from our [highway maintenance] service providers*" (**C1**).

Looking to the future, the participants disagreed on the role of visual inspections to maintain an understanding of bridge condition. Some saw that there would always be a role for visual inspections, perhaps augmented with technology "*...visual inspection will still form the basis of most inspections, quite rightly, with competent trained individuals, but using photographs and video to get an objective image which is then automatically overlain on the existing model, and tracks changes with time.*" (**C13**). Whereas others foresee a time when a combination of technologies would be used to monitor a bridge's condition and predict its future. "*Inspection of bridges, how long are you going to do that for? A year? Maybe two? You don't need to do that anymore. You absolutely don't need to do that anymore. You think you do, because that's what you're used to but, with the technology that's coming on at the moment and the way you can actually pinpoint how a bridge is operating, it's a small step from a piece of infrastructure, to wiring it up, to gathering the data, to analysing it and the only time you will need to do a visual inspection is when you have been told by the computer that there is a problem with this bridge*" (**C15**). The authors note that while 'Damage detection' such as this is a highly valuable aim of monitoring systems, it is difficult to reliably achieve in practice (cf. Webb et al. 2015).

5.3 Monitoring Inspections

In some situations, a structural element requires enhanced data collection (e.g. higher frequency or improved fidelity of data) than that collected during routine visual inspection processes. In such cases, most of the represented organisations would implement a programme of 'monitoring inspections'. The inspection periods would then be reviewed depending on the defect severity, deterioration (on-going) and the element's importance in the asset "*it's a balance between keeping everything safe, and keeping an eye on everything and working within the resources we're given.*" (**C3**).

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5.4 Structural Health Monitoring (SHM)

As one interviewee points out "*The vision we talk about is of a ubiquitous world where, like with the sensors in modern cars, the bridges tell us everything about their performance. I think we've got quite a long way to go to get to that, but it should be an ambition however whether it is a viable and economic vision is still an interesting question"* (**C13**). More recent efforts to put monitoring as central to infrastructure asset management (cf. Middleton et al. 2016; Davila Delgado et al. 2017) mean that many researchers argue that new structural health monitoring technologies will supplant visual inspection as the main type of SHM (e.g., McRobbie et al. 2015; Hoult et al. 2009). SHM systems offer the prospect of reduced levels of traffic disruption as well as the potential for more frequent data-collection points and nodes. The use of SHM systems appears to be limited to instances where a specific structure, critical to the network operation, has a particularly serious defect (e.g., the case of the Hammersmith Flyover: Webb et al. 2014): "*we have specific monitoring, so if we've got a specific problem we're concerned about and we want to gain information about it then we will ...have targeted monitoring, [that] definitely will help with what we need to do ...we're talking about a handful of cases*" (**C2**). Similarly, another interviewee stated: "*we have, probably, a dozen sites where we have real-time monitoring. They're the stuff we're really worried about ...it's not very often, but we do do-it*" (**C5**). While another said that if they were to deploy SHM: "*it would be, very much, targeted*" (**C1**). One interviewee noted the reassurance that monitoring a structure had given them to keep a structure in service: "*given the choice of doing it again, or not doing it, I would definitely implement it again ...for the peace of mind, and really we needed it for BD 79 - we needed some justification to keep the road open*." (**C16**). Some participants reported that they have: "*none [monitoring systems] at the moment ...not any remote monitoring*" (**C11**). However, asset managers with large, strategically important assets to manage use SHM: "*Where do we start? We're monitoring wire breaks ...there's wind speed for bridge closure ...there's the weigh-in-motion system ...*" (**C8**, **C9**). Some of those interviewed indicated that in the future they could be interested in using SHM: "*I am aware of ...remote monitoring as well*" (**C3**), another participant stated: "*we probably don't do as much as we should*" (**C2**). Others - when asked if there is monitoring they would like to do, but currently do not - noted that the condition of their structures does not currently warrant the use of monitoring systems: "*we've not really got anything that is of a serious concern, to say I really want that minute-by-minute*" (**C6**). Others noted the cost of monitoring systems as a deterrent: "*part of it would be cost, so, can we justify putting it in?*" (**C2**), and looked forward to lower-cost commoditised sensors: "*Wouldn't it be good to have a 21st Century Inspectors Toolbox, ... a box of various cheap widely available and easy to connect sensors?"* (**C12**). It was also noted that "*the use of the data's the key thing, and what I found is when it came to the assessment stage, the use of this data was very poor" (**C13**)* and that in specifying systems, managers need to ask themselves *"what is this monitoring really going to tell you?*" (**C5**).

Several participants anticipated an increase in the use of image processing techniques to augment and replace more traditional monitoring and inspection methods: "*without question augmented reality and virtual reality are going to be absolute game changers. Computer vision is a no-brainer.*" (**C13**). One participant noted positive results from replacing traditional strain gauges with digital image correlation (DIC) "*We've been doing a combination of strain gauging and digital image correlation to take multiple strain fields over difficult to access areas such as over the railway line. That's a technique we're using more and more, actually* (**C14**)."

5.5 Load-rating assessments

Some participants identified a link between structural condition and assessment of structural capacity: "*There*'*s interaction between the two sides, so it may be that an assessment triggers an additional inspection. Examination may trigger assessment* [which is] *more likely than assessment triggering an examination*" (**C5**) and one suggested change in condition can trigger a reassessment of load-rating: "*so it*'*s as things change, or we're aware of some deterioration that effects the assessment, then we look at reassessing*" (**C3**). Verification of the results of structural analysis is another use of monitoring data (i.e. 'Model Validation' (Webb et al. 2015)): "*as part of the assessment process, we do use strain gauges or whatever, so we can back analyse*" (**C5**).

6. USES OF BRIDGE ASSET DATA: MAKING DECISIONS

The linkage between the recorded data and its use in informing management decisions was noted by some participants in the study: "*[the database] is just a repository for data, and perhaps some information, the knowledge is how you use it, and the wisdom is implementing that*" (**C1**). Figure 5 shows the branch of the developed HPM for 'Making Decisions' again with four primary nodes represented 'understanding need'; 'identifying interventions'; 'prioritising work' and 'planning interventions'.

6.1 Identifying and Prioritising Need

The most commonly reported use of bridge condition data is to determine the need for maintenance interventions. "*So we get a great big long list [element by element, across all structures], so we can look at that and say those are the sorts of things we need to be looking at, and that*'*s a first pass*" (**C2**). One interviewee reported that they rely on contractors to identify renewals: "*A lot of it relies on our service providers ...to identify need*" (**C1**).

Monitoring data too is used to identify needs and target interventions to resolve them: "*Take the example of acoustic emissions - we collate the data so we know where the highest instances of wire breaks is ...if we did get a cluster of wire breaks, then obviously when we went in to do our next intrusive inspection, then that [data] would feed into the selection of the panels for the intrusive inspection*" (**C9**).

6.2 Analysing Trends

The asset owners expressed a desire to monitor trends in sub-groups of their stocks: "*we look at trends at a family level, so for this family of structures we have the probability of a structure falling from one condition grade to the next*" (**C12**). The ability to analyse trends may be an area for innovation "*so we look at trends in condition ...but it's mainly used at a strategic level and obviously what we want to do is to be able to look at trends at an operational level as well ...looking to the future, there's a lot more opportunity to use the data in much smarter ways ...we're not probably very good at looking at trends, so it relies on individual's judgement to say whether we've got problems with particular types of structures*" (C1).

6.3 Maintaining an Audit Trail

Another use of the collected data is to provide evidence to justify what work to do and that work needs to be done: "*we have a finite resource; it's about justifying where's the best place to spend it*" (**C2**). Another interviewee also explained that the data can be important in justifying why sometimes work is not carried out: "*that priority score also helps us defend not doing something to politicians or the public*" (**C3**).

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6.4 As a Contractual Tool

In some cases, the asset owner delegates some management decisions to contractors who are charged with maintaining the asset for a given timeframe. Therefore, asset owners' have an interest in ensuring that long-term performance of structures is engendered by the decision making process. Representatives from two organisations explained that such contractual terms related to the condition of the assets: "*we have to hand it back in a condition which allows it to be operated for the remainder of its design life*" (**C9**) and one interviewee noted contractual terms that specifically mention condition data "*on a fixed date at the end of the contract they have to hand back all structures with a BCI score of 90 or above*" (**C6**).(Note to reader, *BCI* = Bridge Condition Index and a score of 90 or above indicates a structure is in very good condition see Sterritt & Shetty, 2002 and Atkins 2007). Another interviewee suggested that their organisation could be interested in using condition metrics in future contracts with service providers to monitor performance.

7. TAKING MANAGEMENT DECISIONS

Some common themes were identified across the organisations studied with respect to management decisions (despite variability in systems and processes): (i) 'Prioritisation Processes'; (ii) 'Lifecycle Planning'; (iii) 'Standard Asset Operating Policies' and (iv) 'Engineering Judgement'.

7.1. Prioritisation Processes

For some organisations, prioritisation of work is quite a simple process: "*the priority is often very simple ...we've a high, medium or low priority*" (**C5**) other bodies adopt quantitative approaches: "*we've got our own priority scoring system ...Which relates to the importance of the element, the severity of the defect, the size of the structure in terms of deck area, and* *cost*“ (**C4**). One interviewee described the process of prioritisation: “*we have an inspection programme, which highlights defects in structures, which generates what we call a risk score ...those highest risk scores go forward to a renewals programme and what we then try and do is, through Value Management, prioritise those renewals*“ (**C7**). At least two interviewees referred to a “Value Management” process in their organisations but there were differences in whether such processes are used to prioritise interventions or study options. Not all organisations incorporated cost at this stage. Some attempted to determine what may be termed ‘ratio of risk reduction per pound of spend’: “*effectively, we start off with the three risk categories and then we prioritise on that, and then we ...put the costs against each of those items there, and then we get a value ratio*“ (**C2**). While another approach involves estimating the ratio of future expected savings in terms of whole life cost divided by immediate cost – analysed in conjunction with risk scores.

Some of the owners had an aspiration for computer systems to combine deterioration modelling and condition monitoring to automatically produce a prioritised maintenance plan, there was scepticism as to whether it is possible at stock level with current technology maturity: “*I don*‘*t believe we’ve got a level of sophistication within that arena to begin to determine what your prioritised programme of interventions are.*“ (**C15**). However, such systems were reported to be in place for one flagship project on an individual structure: “*they tend to be slightly bespoke, but there are decision support tools stuck to certain structures. ...the decision support tool [for one strategically important structure] looks at extrapolated condition as one thing, but it*‘*s only one of many factors. Other important things are the consequence of loss of an asset, the Traffic Management requirements and the benefits of combining with other work. The deterioration curves are used initially to get the initial plan, but then you should get the data to update it ...of course if you’ve got data on corrosion,*

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carbonation, cracking/spalling and you've got a couple of snapshots in time you can fit deterioration curves and then update them with actual data. Again, this is in pockets, I'm not pretending we're doing this across the board" (**C14**).

7.2 Lifecycle Planning

Consideration of the asset lifecycle was common in the surveyed set. For instance, modelling of deterioration effects as well as estimates of whole life cost are used to plan 'preventative maintenance' efforts " *[the system] tries to predict the condition of different elements over the next 30/40 years, which gives us an indication of ...we don't have to do that now, we can do that in 5 years' time etcetera"* (**C4**). One of the surveyed organisations possessed the capability to review the costs and effects of different maintenance strategies for their whole asset stock *"the whole-life-costing's based on our lifecycle plans ...in terms of putting the programme together as a whole ...we will also do an absolute minimum scenario, see what does that look like, we'll run an optimised programme, what does* that look like" (**C2**). Some interviewees reported frustrated attempts to adopt decision support tools based on whole-life costing *"We've tried in the past ...we used to have a system [which] I never got on with because it always came up with the same answer in my mind which was, 'the cheapest option today is the best'"* (**C5**).

7.3 Standard Asset Operating Policies

An asset manager may specify standard operating policies for various types of assets and components. Such a policy may require standard interventions for commonly identified defects as well as prescribing 'trigger levels' (i.e. threshold check, cf. Webb et al. 2015) which when reached (or exceeded) certain types of intervention are undertaken. Such efforts may assist the transition from 'reactive maintenance' to 'preventative maintenance'. As noted by some interviewees: "*so those maintenance manuals will have 'this area once every x* *years' so there's a rolling programme you take out every year*" (**C8**). However, some participants were more sceptical about prescribed maintenance based on standard policies: "*you can make some broad assumptions about deteriorations but you've always got to look at the particular condition of those assets*" (**C1**).

7.4 Engineering Judgement

Those interviewed emphasised that 'engineering judgement' remains critical for decision making: "*Engineering judgement still rules the day*" (**C5**). This chimes with the statement of Shepard "*The appropriate use of technology and a modern BMS should be used strictly as decision support tools—not as a replacement of engineering judgement"* (Shepard, 2005). The importance of peer review was mentioned: "*We have a peer review process to evaluate decisions ...where I have to pitch to my peers*" (**C5**). When discussing the work to be done with a client: "*the list I produce gets discussed at the monthly meetings, so it's pretty much pencilled in at that point which [schemes] are going to be focused on*" (**C11**).

8. CONCLUSIONS

Most of the bridge engineers and managers represented in this survey (and the organisations they represent) remain heavily reliant on visual inspections to monitor the condition of their bridge assets to plan maintenance activities. Use of Structural Health Monitoring (SHM) is limited in practice with the notable exception of targeted cases i.e where the issue to be investigated was already known. The evidence collected from the semi-structured interviews in this paper gives weight to the observation that significant variation exists between the uses of visual inspection data by the industry. It is acknowledged that a larger sample size may reveal more complex and differing trends than those drawn out in this paper. However, the highlights from the interviews presented in this paper and the developed Hierarchical Process

Modelling (HPM) trees do, in the view of the authors, provide a useful insight into the state of bridge asset management practices in the UK.

Although high level inspection standards and guidance, such as BD63/17 (HA, 2017) and the Inspection Manual for Highway Structures (TSO 2007), the interviews indicated little sharing or standardisation of the inspection data interpretation processes which are used to inform decisions. This suggests that asset owners incur extra costs through the needs to develop bespoke processes and to validate their outputs. Many interviewees recognised the potential of new 'smart' technologies for improving the efficiency and effectiveness of bridge inspections and data collection. However, none of the interviewees pointed to a current unifying paradigm for implementing such technologies. This suggests that considerable effort is still required to formulate and implement such a paradigm that would underpin the development of a new marketplace for bridge monitoring and inspection services, founded on the emerging technologies, and delivering more cost effective and reliable solutions to asset owners.

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DATA AVAILABILITY STATEMENT

The relevant quotes taken from each interview are included in this paper after transcription from the recording of each interview. To maintain the anonymity of the interviewed participants, the audio recordings or transcripts cannot be made available in a data repository.

APPENDIX

Table 2 shows the interview protocol used when conducting the semi-structured interviews. Table 3 shows the coding schema used when analysing the interview data.

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TABLE CAPTIONS

Table 1: Details of the interviewees' roles and sectors (adapted from Bennetts et al. 2016)

Table 2: Interview Protocol (running order indicated)

Table 3: Coding Schema applied to the interview data

Table 4: Summary of key findings

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Table 1: Details of the interviewees' roles and sectors (adapted from Bennetts et al. 2016)

Ref.	Interview	Role	Sector	Scope
C1	**1**	Senior Policy Advisor	Highways	Strategic
C2	2	Structures Manager	Highways	Metropolitan Transport Authority
C3	3	Structures Manager	Highways	Local
C4	3	Structures Engineer	Highways	Local
C5	4	Structures Asset Manager	Rail	Strategic
C6	5	Structures Manager	Rapid transit	Metropolitan Transport Authority
C7	6	Regional Structures Specialist	Highways	Strategic
C8	7	Head of Engineering	Highways	Strategic, Concessionaire
C9	7	Assistant Head of Engineering	Highways	Strategic, Concessionaire
C10	8	Researcher	Highways	Local, Heritage
C11	9	Structures Watchman	Highways	Strategic,Service Provider
C12	10	Chief Bridge Engineer	Rail	Strategic
C13	11	Professor	Academia	National
C14	12	Head of Bridge Engineering	Engineering Consultant	International
C15	13	Chief Executive Officer	Highways Concessionaire	Strategic
C16	13	Technical Director	Highways Concessionaire	Strategic
C17	14	Bridge Specialist	Highways	Strategic

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Table 2: Interview Protocol (running order indicated)

Interview Question / Theme	
Introduction	
Q1	What is your role?
Q2	What does your role involve on a day to day basis?
Q3	How long have you been in your current role?
Collection of asset data	
Q4	What data do you collect on your bridge assets?
Q5	How do you collect these data?
Use of asset data	
Q6	How do you use the data that you collect on your structures?
Q7	Are there any IT systems that you use to manage and analyse your data?
The decision making process	
Q8	How do you make decisions regarding the management of structures?
The overall process of managing bridges	
Q9	*Hierarchical Process modelling exercise. (completed on paper)*
Open question	
Q10	Looking at the model we have produced, which aspects of your role keep you up at night?

Table 3: Coding Schema applied to the interview data

Ref.	Code
00	**Great Quotes**
1	**Data collected on assets**
1.1	Monitoring
1.1.1	SHM
1.2	Visual Inspection
1.2.1	Risk based inspection intervals
1.2.1	Reliability of visual inspection
1.3	Inventory data
1.4	Maintenance actions
1.5	Prioritisation of inspection effort
2	**How is data collected**
3	**How is data recorded**
3.1	Database
4	**IT systems used**
4.1	Recent or up-coming changes to IT systems
5	**How is data used**
5.1	Identifying need
5.2	Trends in data
5.3	Future aspirations
5.4	Tool for measuring service provider performance
5.5	Audit trail
5.6	Producing condition scores
5.7	Model validation
5.8	Targeting further testing/inspection
5.9	Informing assessment
6	**How are decisions made**
6.1	Judgement
6.2	Deterioration modelling
6.3	Value for money
6.4	Standard maintenance periods/plans
6.5	For assessment work?
6.6	Assumptions on lifespan?
6.7	Prioritisation
6.8	Asset lifecycle planning
6.9	Whole life cost
6.10	Peer Review
6.11	Heuristics
7	**HPM Exercise**

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Table 4: Summary of key findings

Finding	**Summary of support**
Most organisations remain reliant on visual inspections to monitor the condition of their bridges.	All interviewee's responses support this conclusion
The use of SHM is limited, except for targeted monitoring where there are known issues.	No current monitoring reported – **C3**, **C4**, **C6** Examples of targeted monitoring on a small number of specific structures - **C1**, **C2**, **C5**, **C7**, **C11**, **C12**, **C15** Significant monitoring systems on a large portion of the assets managed **C8**, **C9**, **C10** (it is notable that each of these interviewees are responsible for small numbers of complex assets)

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FIGURE CAPTIONS

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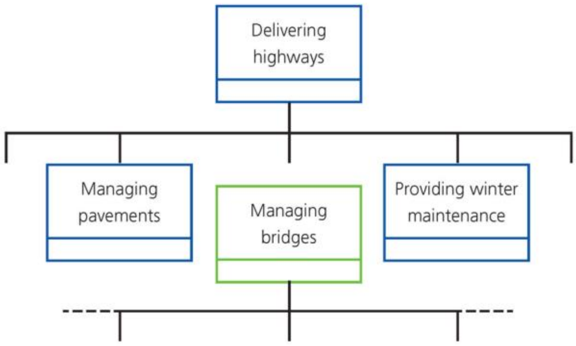

Figure01

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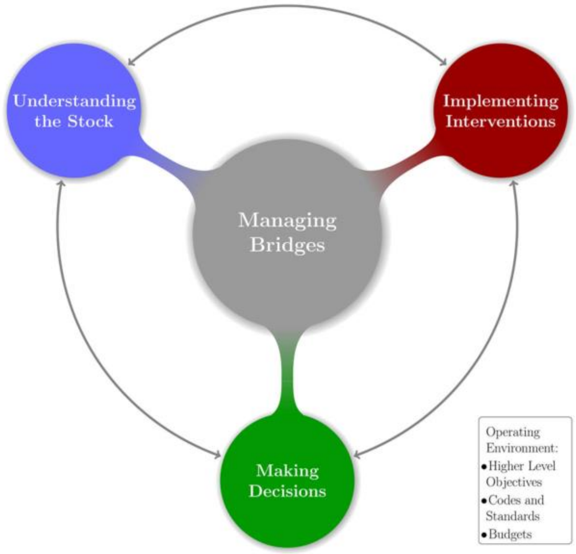

Figure02

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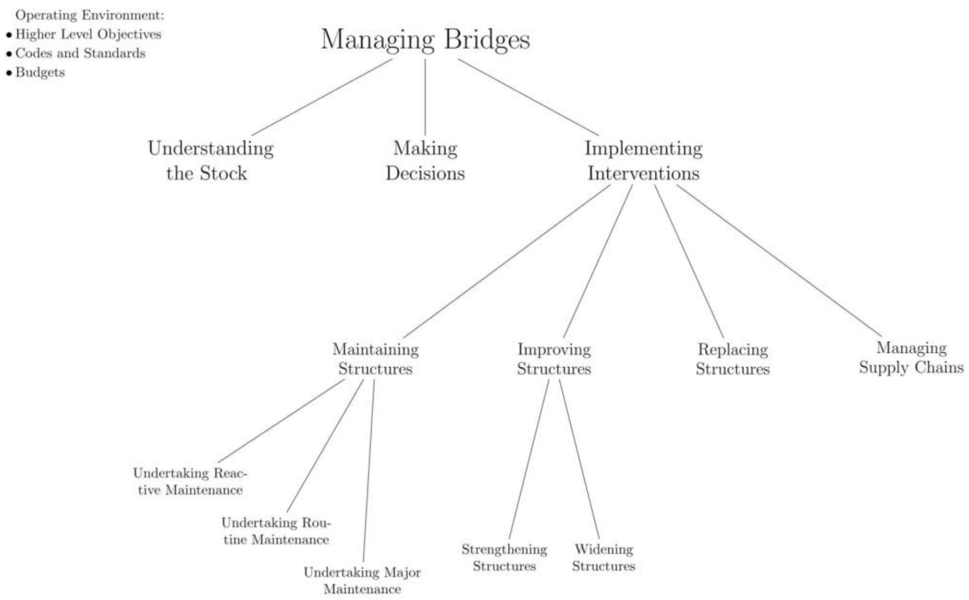

Figure03

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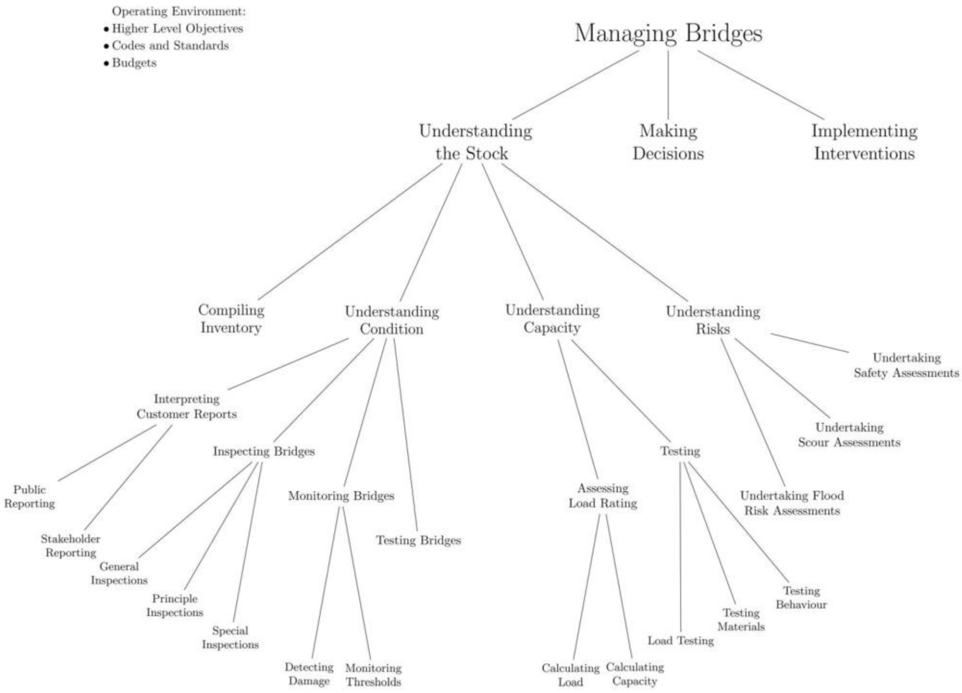

Figure04

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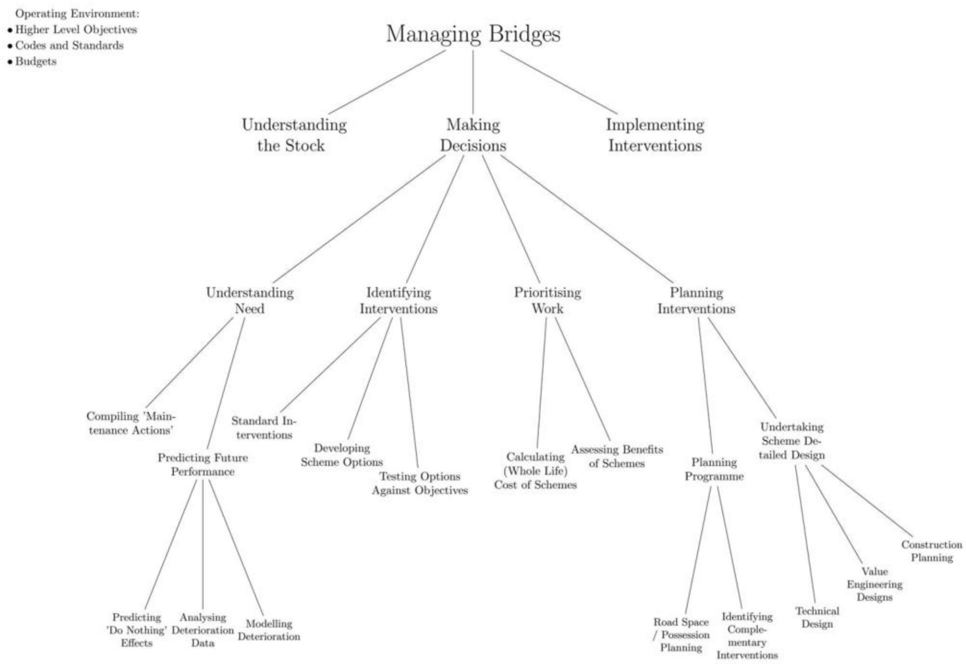

Figure05